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Takeoff Predictions for Powered-Lift Aircraft

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ABSTRACT

Takeoff Predictions for Powered-Lift Aircraft

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Takeoff predictions for powered-lift short takeoff (STO) and conventional takeoff (CTO) aircraft have been added to NASA AMES Research Center's Aircraft Synthesis (ACSYNT) code. The new computer code predicts the aircraft engine and nozzle settings required to achieve the minimum takeoff roll. As a test case, the code predicted takeoff ground rolls and nozzle settings for the YAV-8B Harrier that compared well with measured values. Brief analysis of takeoff performance for an Ejector, Remote Augmented Lift, Hybrid-Tandem Fan, and Vectored Thrust STO aircraft using the new routine will be presented.

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

ACCELM - minimum acceleration required along the flight path

C_D - drag coefficient = $D/(q*S_{REF})$

c.g. - aircraft center of gravity

C_L - lift coefficient = $L/(q*S_{REF})$

D - aircraft drag vector

DFRONT - distance the front thrust vector is from the c.g.

DRAMD - distance of the ram-drag vector is from the c.g.

DREAR - distance of the rear thrust vector is from the c.g.

FA - force along the flight path

FAZ - force normal to the flight path

L - aircraft lift vector

MU - runway coefficient of friction

q - dynamic pressure

RAMD - ram-drag vector

RD - ram-drag vector

SPLIT - thrust split between the forward and rear nozzle

S_{REF} - aircraft wing area

T_F - front thrust vector

THRSTU - uninstalled engine thrust

T_R - rear thrust vector

W - aircraft weight

X_F - x-distance the front thrust vector is forward of the c.g.

X_R - x-distance the rear thrust vector is aft of the c.g.

X_{RD} - x-distance the ram-drag vector is forward of the c.g.

Z_F - z-distance the front thrust vector is above the c.g.

Z_R - z-distance the rear thrust vector is above the c.g.

Z_{RD} - z-distance the ram-drag vector is above the c.g.

γ - aircraft flight path angle

γ_{RW} - runway angle (positive is uphill)

β_7 - angle from c.g. location to front thrust location

β_8 - angle from c.g. location to rear thrust location

β_9 - angle from c.g. location to ram-drag location

θ_F - front nozzle angle with respect to the fuselage (0° is full aft)

θ_{FUS} - fuselage angle with respect to the runway

θ_R - aft nozzle angle with respect to the fuselage

ρ - density of the air

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INTRODUCTION

Current work in the design of powered-lift short and vertical landing (STOVL) aircraft requires r predictions of takeoff performance. The requirem imposed by the ground-roll constraints inherent in the mission of these aircraft. However, data on the fligh takeoff characteristics of these powered-lift jet airc are generally limited. Except for some wind tunnel da such data are nonexistent for many of the new designs bei considered. Additionally, the much more sophisticate engines or thrust deflection devices that will be needed i many of these designs are still in development. This means that predicting takeoff performance is very difficult and that actual performance simulations are impossible for these aircraft. Hence, there is a need for a computer program that will make these predictions with a minimum of input data.

This paper will present the equations and methods used in the new routine, which was incorporated into the Aircraft Synthesis (ACSYNT) computer code developed at NASA AMES Research Center, to predict takeoff parameters. The takeoff performance predictions for four designs that are currently being studied at NASA AMES will be presented.

BACKGROUND

ACSYNT is the conceptual aircraft design code[1,2] that is currently being used at NASA Ames Research Center, and now Cal Poly, to design and study aircraft in the conceptual design stage. It uses both empirical and analytical methods to predict aircraft weight and performance parameters, given individual mission phases. These mission phases can be any combination (up to a maximum of twelve) of the following:

1) Takeoff
2) Climb
3) Acceleration
4) Cruise
5) Loiter
6) Combat
7) Descent
8) Hover

Previously, ACSYNT had two options to predict takeoff performance for a given aircraft. One was a very simple and fast preliminary estimate that required only weight information, while the other was a simulation routine that required the actual weight and rotation velocity, and for the case of powered-lift STO aircraft, the actual thrust-nozzle angle schedule versus aircraft velocity and/or height.

The first method mentioned is an empirical method that will estimate a takeoff ground roll given only the aircraft's weight. It does this by comparing its weight to that of other (and usually older) aircraft to find what its takeoff ground roll is likely to be.

The latter routine uses a time-step integration method that simulates an aircraft's takeoff and transition to wing-borne flight. Unfortunately, this simulation requires specific thrust and device settings that cannot be known for conceptual aircraft. This means that the code will let the aircraft fly in an unbalanced condition if the exact engine, flap, and nozzle settings are not input. It also does not allow for analysis of most of the powered-lift STO aircraft currently under study--even if all the nozzle schedules, etc. were known. This routine gave ACSYNT little capability to optimize takeoff and did not allow for constraints to be imposed on many of the takeoff conditions. Therefore, a third and different program was needed to predict the ground roll, aircraft thrust deflection angles, and/or thrust split between the thrust vectors, given minimal input and constraints for takeoff.

Unlike conventional takeoff (CTO) aircraft, powered-lift aircraft can deflect thrust at various angles to the fuselage. This unique ability enables powered-lift aircraft to take off at much lower speeds, which requires less ground roll, but complicates the prediction of takeoff performance. For example, a powered-lift aircraft that has independent thrust vectoring both forward and aft of the c.g. not only has all the unknowns of CTO aircraft (takeoff velocity, flap settings, tail settings, and rotation speed), but the additional unknowns of front thrust-vector angle, rear thrust-vector angle, and thrust split. Many powered-lift aircraft also have additional ram-drag from the deployment and operation of the thrust-deflection device as well as propulsion systems that operate differently during wing-borne and jet-borne flight.

TAKEOFF PROGRAM

Requirements

The requirements for the new takeoff routine were that it should predict, for powered-lift aircraft, the front-nozzle angle, the rear-nozzle angle, and the thrust split that give a minimum takeoff ground roll. It should also predict the minimum ground roll for CTO aircraft. The routine was also required to be efficient in terms of computer run time, to be integrated into ACSYNT, to use predicted parameters from ACSYNT, to be as accurate as possible (given input data), to allow for many different aircraft configurations, and to require minimum additional input.

Assumptions and limitations

In order to work within the scope of the above requirements, some assumptions and limitations had to be imposed. The effects of a reaction control system (RCS) were not taken into account since the reduction in engine performance, from the bleed air required by the RCS system, is not linear and depends on the aircraft configuration. Since moments of inertia are not easily calculated for conceptual aircraft, the aircraft was assumed to be a point mass acting at the c.g. All aerodynamic moments were assumed to be negligible relative to the thrust moments. This means that all lift and drag forces act at the c.g., that tail or canard moments can counter the pitching moment of the wing, and that the aircraft is balanced using only thrust forces. The user may specify total aircraft lift and drag data or use the values predicted by ACSYNT. The rear nozzle angle is allowed to vary from 0° to 180°.

The forward thrust was allowed to vary linearly with respect to the thrust split. Although this linearity was not an accurate assumption, it was necessary for the simplification of calculations and input. Only single engine aircraft may be analyzed. Ground effects, which are not fully understood and not easily applied, were neglected.

Program description

Figure 1 shows all the forces and their locations relative to the fuselage which are used in the takeoff program. Only the front thrust vector and the rear thrust

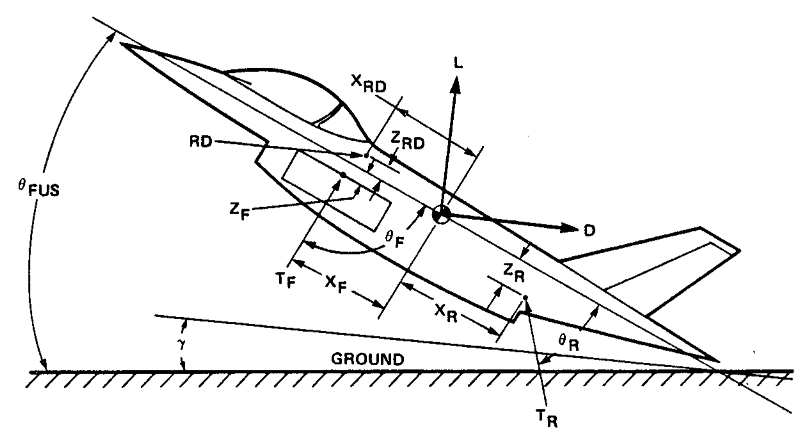


Figure 1 Aircraft free body diagram used in the takeoff program

vector are used in balancing the aircraft. The user may specify such inputs as the angle range of the front nozzle, the limit on the thrust split, the flight path angle, and the acceleration required along the flight path at takeoff. Initial nozzle and flap angles may also be specified for the ground roll preceding takeoff (see Appendix A for input details). There are basically three equations that are used for predicting an aircraft's forward-nozzle angle, aft-nozzle angle, velocity, and thrust split for minimum takeoff roll. The first equation is the balance equation about the aircraft's c.g. created by the ram-drag vector, front thrust vector, and rear thrust vector. The moments are summed about the c.g. (Figure 2) with positive moments in the clockwise direction and positive forces acting in the direction of the forward flight path.

$$\text{THRSTU*SPLIT*DFRONT*sin}(\Theta_F-\beta_7)\text{-RAMD*DRAMD*Sin}(\gamma-\Theta_{FUS}-\beta_9) \quad (1)$$

$$= \text{THRSTU * (1-SPLIT) * DREAR * Sin}(\Theta_R+\beta_8) \quad \text{where,}$$

$$\text{DFRONT} = \{(X_F)^2 + (Z_F)^2\} \quad (1a)$$

$$\text{DREAR} = \{(X_R)^2 + (Z_R)^2\} \quad (1b)$$

$$\text{DRAMD} = \{(X_{RD})^2 + (Z_{RD})^2\} \quad (1c)$$

$$\beta_7 = \text{atan}(\frac{Z_F}{X_F}) \quad (1d)$$

$$\beta_8 = \text{atan}(\frac{Z_R}{X_R}) \quad (1e)$$

$$\beta_9 = \text{atan}(\frac{Z_{RD}}{Z_{RD}}) \quad (1f)$$

The second equation is the sum of the forces perpendicular to the flight path. This summation is set to zero, insuring that the aircraft is on the specified flight path:

$$FAZ = 0 = C_L*q*S_{REF} - W*Cos(\gamma) + THRSTU*SPLIT*Sin(\theta_{FUS}+\theta_F-\gamma) + THRSTU*(1.0-SPLIT)*Sin(\theta_{FUS}+\theta_R-\gamma) \quad (2)$$

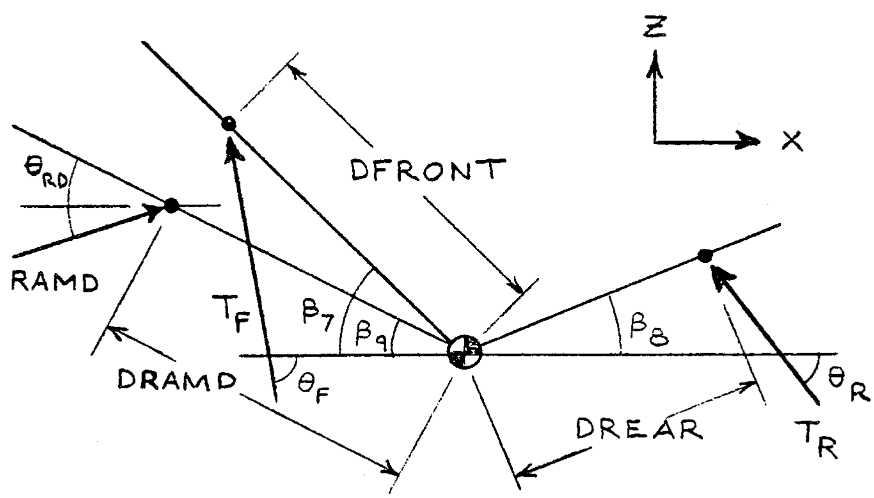


Figure 2 Free body diagram used for the balance equation.

The third equation is the sum of the forces along the specified flight path. This summation is set equal to the input flight path acceleration times the aircraft weight:

$$FA = W*ACCELM = - C_D*q*S_{REF} - RAMD - W*Sin(\gamma) + THRSTU*SPLIT*Cos(\theta_{FUS}+\theta_F-\gamma) + THRSTU*(1.0-SPLIT)*Cos(\theta_{FUS}+\theta_R-\gamma) \quad (3)$$

If Eqs. (1), (2), and (3) are not satisfied, then the aircraft cannot take off given all the input takeoff conditions. Initially the unknowns are ground roll, takeoff velocity, front nozzle angle, rear nozzle angle, and thrust split. Since there are five unknowns and, at this point, only three equations, two more equations are needed to solve the problem. These two equations will not be equations in the normal sense, but conditions placed on the problem.

<u>CONDITION 1:</u> to minimize takeoff velocity given flight path acceleration.

<u>CONDITION 2:</u> minimizing takeoff velocity will thus minimize ground roll (see equation 4a).

The latter is true since ground roll is a function of the velocity.

Due to the nature of the problem the predictions for thrust split, front and rear nozzle angles, takeoff velocity, and ground roll must be found by an iterative process. Using Eqs. (1), (2), and (3) along with condition 1, all the unknowns are solved except ground roll. When the above iteration converges to a minimum takeoff velocity, ground roll is then computed by integrating the forces acting on the aircraft for a velocity of zero to the takeoff velocity:[3]

$$SG = \int_0^{V_{TO}} \frac{V}{a}\, dV \tag{4a}$$

where,

$$a = \frac{[THRSTH - MU*(W - THRSTV) - RAMD] - [C_D - MU*C_L]*q*S_{REF} - W*\gamma_{RW}}{W/g} \tag{4b}$$

This ground roll is then the minimum ground roll for the aircraft (condition 2) given input conditions and program assumptions.

The iterative process used to calculate the minimum takeoff velocity, and thus ground roll, is shown in Figure 3 and described as follows:

1. The front nozzle angle is estimated.
2. The takeoff velocity is estimated.
3. The thrust split and rear nozzle angle are solved using the first two equations, (1) and (2), as follows:

$$\Theta_R = \mathrm{ArcSin}\left(\frac{\mathrm{THRSTU*SPLIT*DFRONT*Sin}(\Theta_F-\beta_7) - \mathrm{RAMD*DRAMD*Sin}(\gamma-\Theta_{FUS}-\beta_9)}{\mathrm{THRSTU*(1.0-SPLIT)*DREAR}}\right) - \beta_8 \quad (5)$$

$$\mathrm{SPLIT} = \frac{\{\mathrm{Sin}[\mathrm{ArcCos(LHS)} - \Theta_{FUS}+\gamma+\beta_8]\}*\{\mathrm{THRSTU*(1.0-SPLIT)*DREAR}\} + \mathrm{RAMD*DRAMD*Sin}(\gamma-\Theta_{FUS}-\beta_9)}{\mathrm{THRSTU*DFRONT*Sin}(\Theta_F-\beta_9)} \quad (6)$$

where LHS is defined in appendix B.

4. The takeoff velocity is then solved for using Eq. (7) and the currently calculated values for the thrust split and rear nozzle angle:

$$V^2 = \frac{W + \mathrm{RAMD*Sin}(\gamma) - \mathrm{THRSTU*SPLIT*Cos}(90-\Theta_F-\Theta_{FUS}) - \mathrm{THRSTU*(1.0-SPLIT)*Sin}(\Theta_{FUS}+\Theta_R)}{0.5*\rho*S_{REF}*(C_L*\mathrm{Cos}(\gamma)-C_D*\mathrm{Sin}(\gamma)} \quad (7)$$

5. If this takeoff velocity is not the same as the previous value, then this value is the new estimate. However, if the squared velocity is negative, then make new estimate = previous

estimate + 0.1*previous estimate (iterate less than 30 times).

6. Steps 3 through 5 are repeated until takeoff velocity converges. If no convergence, then a message is printed stating this fact along with probable causes.
7. Next, another front nozzle angle is tried--using an improved estimate.
8. Steps 2 through 5 are repeated until the minimum takeoff velocity is found.

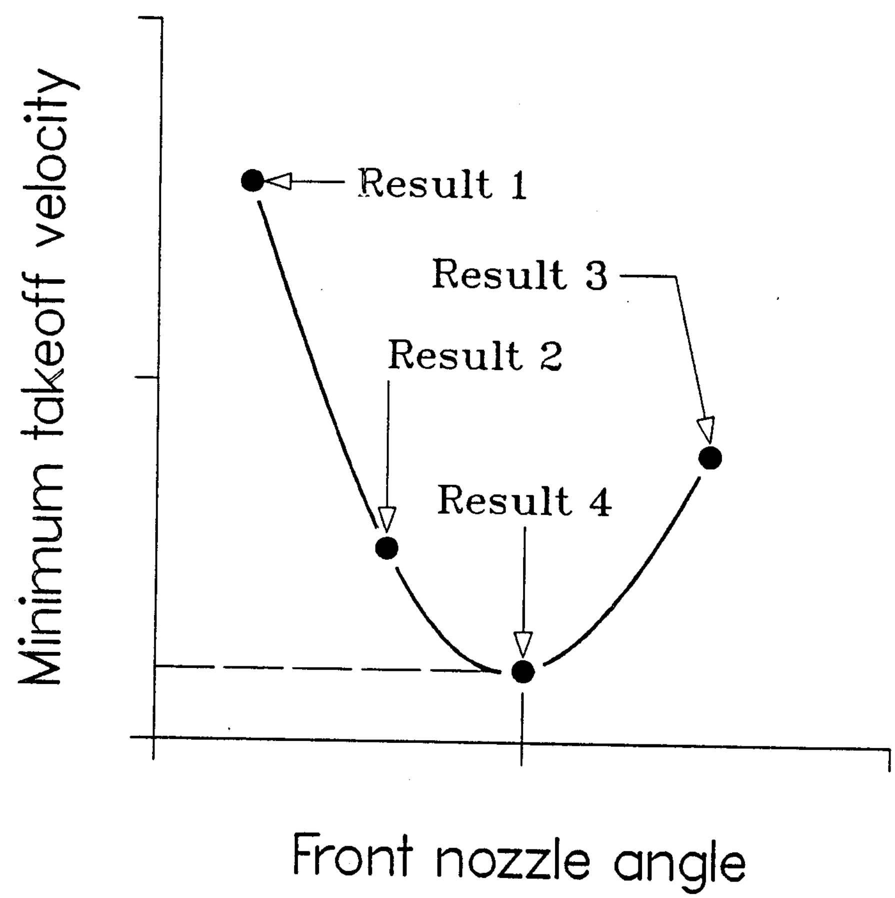


Figure 3 Ground roll minimization technique.

9. The computed takeoff velocity is then multiplied by some safety factor (input by user). This velocity is the predicted minimum takeoff velocity.
10. The ground roll is then calculated by integrating aircraft forces, as described earlier (equation 4a), from a velocity of zero to the takeoff velocity.

To allow for the takeoff analysis of many types of aircraft, two other iteration procedures were also used--one very similar to the one described above (again for powered-lift aircraft), and a much simpler one for CTO aircraft. The first routine, as described above, is for powered-lift aircraft with non-coupled front and rear nozzles (i.e. the front and rear nozzles can move independently of one another) with a variable thrust split between these nozzles.

For aircraft with the front and rear nozzles coupled, such as the Harrier, a simpler technique is used. Here the thrust split is set to 0.50 and the front and rear nozzles are coupled. The process is then similar to the one previously described, except step one is removed and step three only solves for the nozzle angle. This routine converges very rapidly as compared to the first.

The third routine is a very simple procedure used for CTO (conventional takeoff) type aircraft--aircraft with no powered-lift devices. This routine is almost solved explicitly--only ram-drag need be iterated on. See appendix A for more details.

PROGRAM VALIDATION

To validate the takeoff routine, actual data for a STOVL fighter is needed. Since the AV-8B Harrier is the only operational STOVL fighter it was chosen--or more specifically, the YAV-8B Harrier was chosen--as the test case. For this comparison the takeoff program requires engine thrust, total lift and drag data (before and during takeoff), wing incidence angle, fuselage attitude during ground roll, angle of attack, initial nozzle setting during ground roll, and acceleration along the flight path at takeoff. If this were a conceptual design, the input data mentioned above would be ACSYNT estimates and/or user estimates. Since the YAV-8B is an actual aircraft, this data is known and, when input into ACSYNT, should give accurate results. For the YAV-8B, the engine thrust at takeoff is 21,810 lb. During the ground run, $C_L = 0.675$, $C_D = 0.55$, and, at takeoff, $C_L = 1.13$ and $C_D = 0.319$; both C_L and C_D are for an angle of attack of 9.5°.[4] The wing incidence is +3° relative to the fuselage, and the fuselage is at +6.5° relative to the runway. The initial nozzle setting is 10°, and the flight-path acceleration varies with gross weight (actual acceleration numbers were obtained from the takeoff analysis performed by Hahn and Wilson[5]).

Takeoff ground roll data as a function of gross weight are shown in Figure 4. The program predicted slightly shorter takeoff ground rolls than reported,[6] possibly a result of the assumption of instantaneous nozzle rotation--the Harrier actually takes about a quarter of a second to rotate its nozzles to the takeoff position.

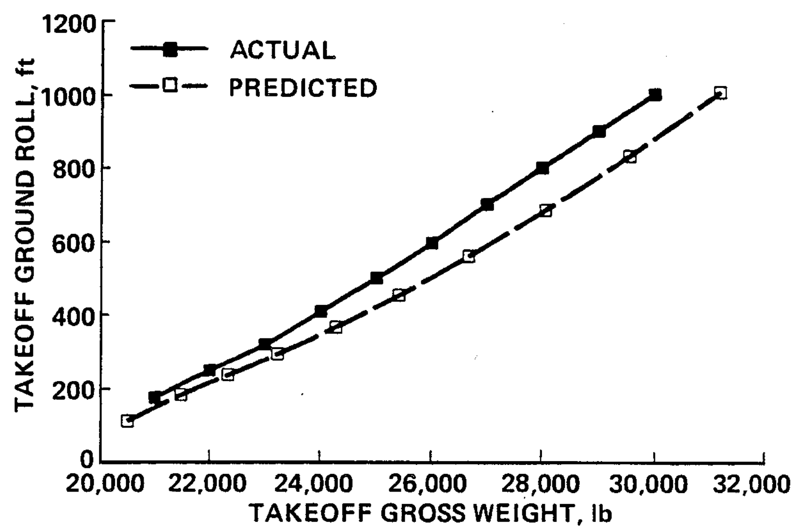


Figure 4 Predicted and actual Harrier takeoff ground rolls versus takeoff gross weight.

For the minimum takeoff roll, optimum thrust angles predicted by the code are compared to known takeoff data in Figure 5. The data in Figure 5 corresponds to the takeoff ground rolls in Figure 4. The nonlinearity of the predicted nozzle-angle was due to convergence tolerance throughout the takeoff routine and again the assumption of instantaneous nozzle rotation. Both the takeoff ground roll and the nozzle angle predictions for the YAV-8B were very good. Data in both figures are for zero wind on a level concrete runway.

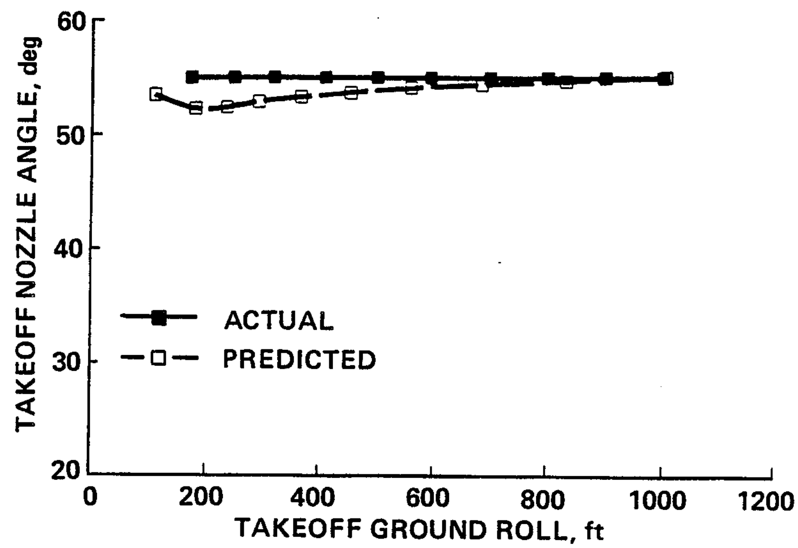


Figure 5 Predicted and actual Harrier takeoff nozzle angles versus takeoff ground roll.

AIRCRAFT DESCRIPTION

The four aircraft takeoff concepts that were analyzed using the takeoff routine were the Ejector, RALS (Remote Augmented Lift System), Hybrid Tandem Fan, and Vectored Thrust.

Ejector concept

The Ejector concept (Figure 6) is very similar to the General Dynamics E7 concept. It uses an ejector with an augmentation ratio of 1.5 in each wing root that, when activated, uses bleed air from the second stage of the engine compressor. The augmentation ratio of the ejector is defined as the measured vertical thrust divided by the installed

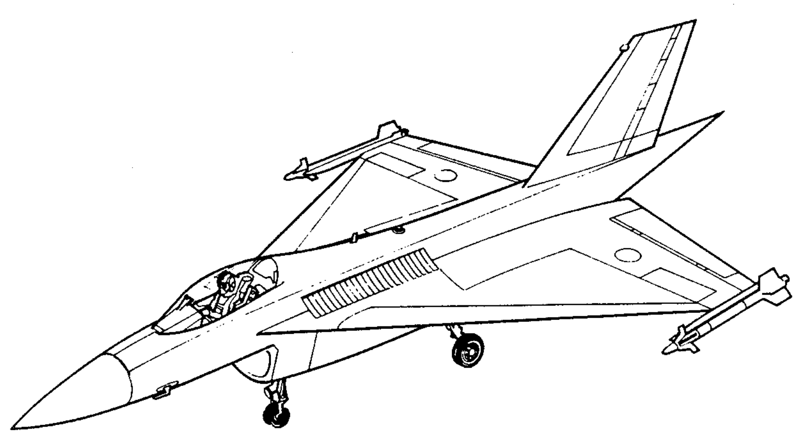


Figure 6 Ejector aircraft.

engine thrust. An assumption for the mass flow ratio (secondary to primary) of 10:1 was used for ram-drag calculations.[7] The ejector design and propulsion system are shown in Figures 7 and 8.

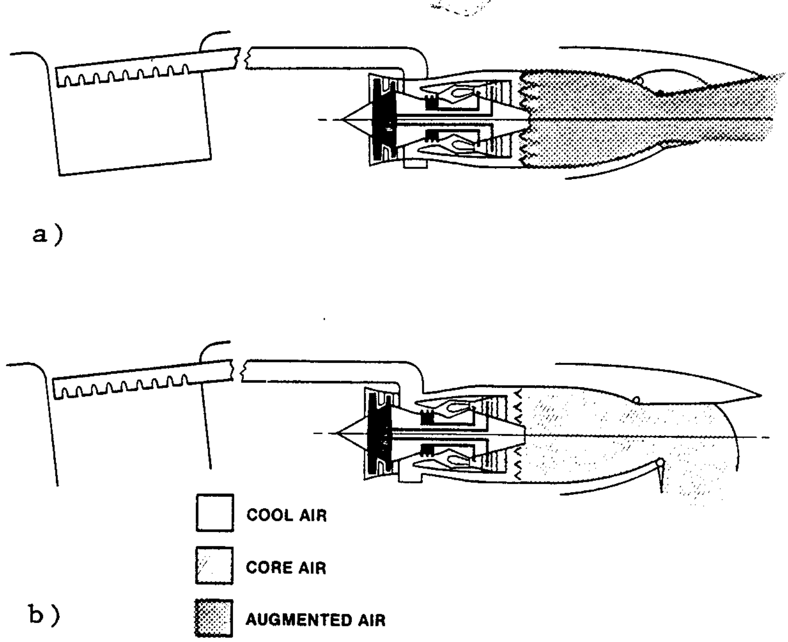


Figure 7 Ejector engine system: a) nonpowered-lift configuration, b) powered-lift configuration.

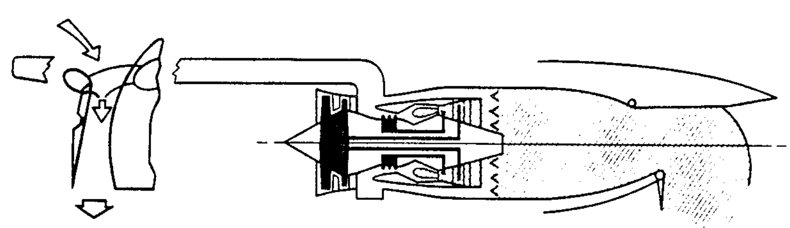


Figure 8 Operation of Ejector mechanism.

From these two figures it can be seen how the fuselage and lower part of the wing are used as a diffusing and mixing chamber for the ejector. The reduction in wing area while the ejectors are operating is unknown and not taken into account for this study. For this concept, the center of thrust for the ejectors and their respective ram-drag were located four feet forward of the c.g., the rear vectoring nozzle was four feet aft of the c.g., and the waterline for each was assumed to be identical (probably a bad assumption since their relative vertical positions can have a large affect on takeoff ground roll).[8] Also, the ejector thrust vector is fixed at 90° to the fuselage.

The aft-nozzle of the engine is an ADEN type nozzle and can be afterburned as needed. The ADEN nozzle is an advanced single nozzle concept that allows thrust vectoring from 0° to more than 90°. The powerplant is a dual cycle jet engine that operates differently between vertical (ejector) and up-and-away (non-ejector) flight.

Remote augmented lift concept

In the remote augmented lift (RALS) concept the ejectors are replaced by a single vectoring-nozzle located behind the pilot in the fuselage (Figure 9). For this concept the nozzle can vary from -15° to +30° from the normal of the fuselage. The RALS engine configuration is shown in Figure 10, and as can be seen, is very similar to the ejector engine configuration. The rear nozzle is now a ventral nozzle instead of the ADEN type nozzle used in the ejector and as also shown in Figure 10; though, full afterburning is still allowed.

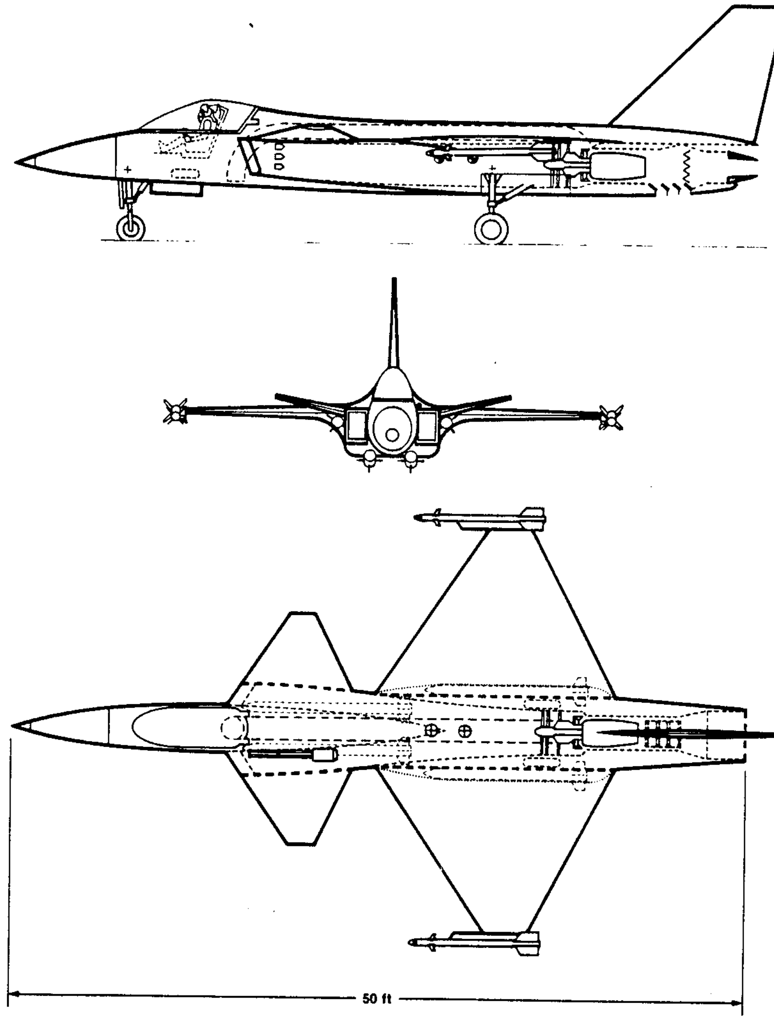


Figure 9 RALS aircraft.

The ventral nozzle also allows thrust vectoring, but accomplishes this by regulating the air flow between two aft nozzles--one at the rear parallel to the fuselage, and the other forward of this position but behind the c.g. and perpendicular to the fuselage. For thrust forward of the aircraft's c.g., air is bled from the engine compressors and, as with the ejector engine, is routed to the forward nozzle by a series of ducts. In this case, burning is allowed in the nozzle up to an exhaust gas temperature of 2000° F.

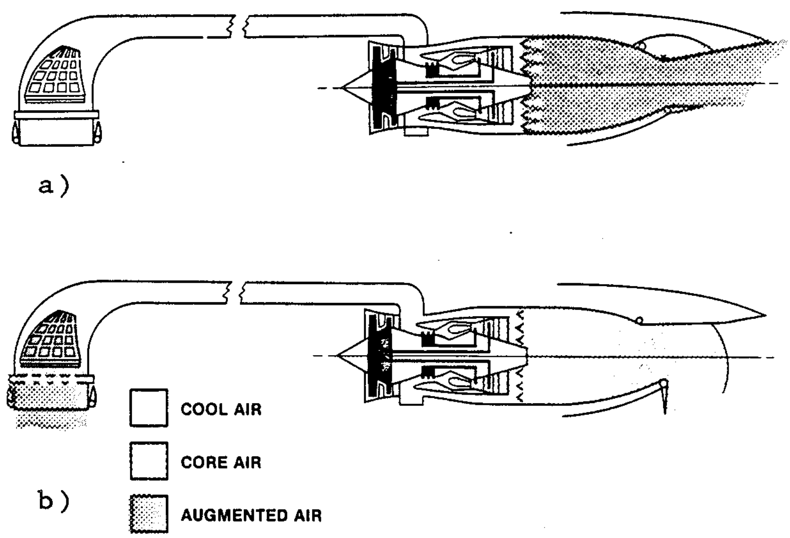
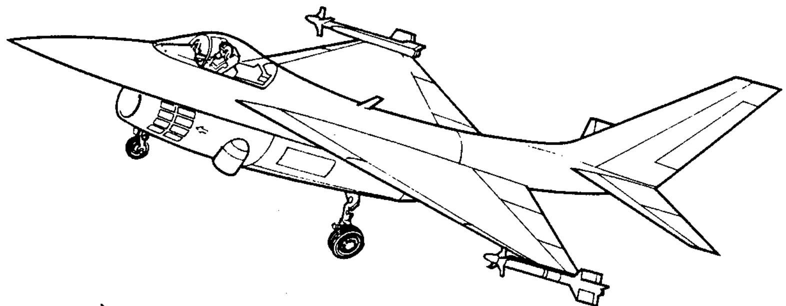


Figure 10 RALS engine system: a) nonpowered-lift configuration, b) powered-lift configuration.

Hybrid-tandem fan concept

The hybrid-tandem fan concept, as shown in Figure 11, also uses a multi-mode engine concept (Figure 12) that, instead of routing air from the fan of the engine for thrust forward of the c.g., places the fan slightly ahead of the forward thrust point. When forward thrust is needed the engine vectors part of the fan air downward (Figure 12b). An additional complication this engine has, as compared to the previous two, is that in order to place the fan just ahead of the forward thrust point and keep the rest of the engine towards the aircraft c.g., part of the compressor must be stretched from 7 to 12 feet. To deflect the rear thrust, it uses an ADEN type rear nozzle similar to the ejector concept.



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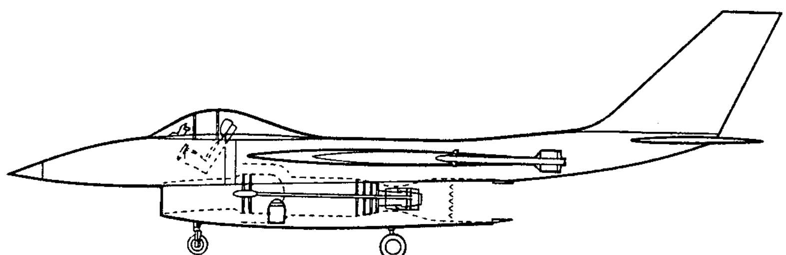
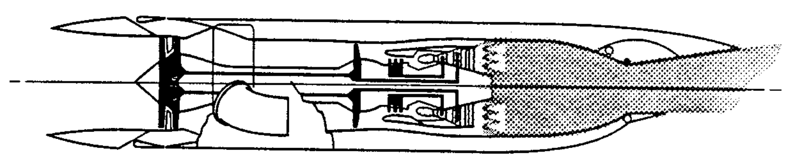


b)

Figure 11 Hybrid Tandem Fan concept
a) isometric view. b) side view.



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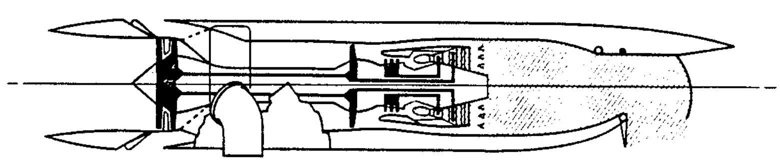

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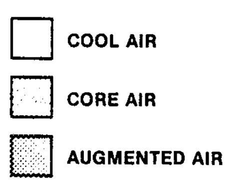

Figure 12 Hybrid Tandem Fan engine system: a) nonpowered-lift configuration, b) powered-lift configuration.

Vectored thrust concept

The vectored thrust concept is similar to the Harrier relative to thrust vectoring. Both the front and rear nozzles are coupled (i.e. if one moves 10°, the other moves 10°). The engine (Figure 13) is located at the aircraft's c.g. and has a thrust split of approximately 0.5. Burning can be allowed in both nozzles and all nozzles are operating all times. This means a simpler uni-mode engine can be used as opposed to the more complex multi-mode engines of the other three aircraft.

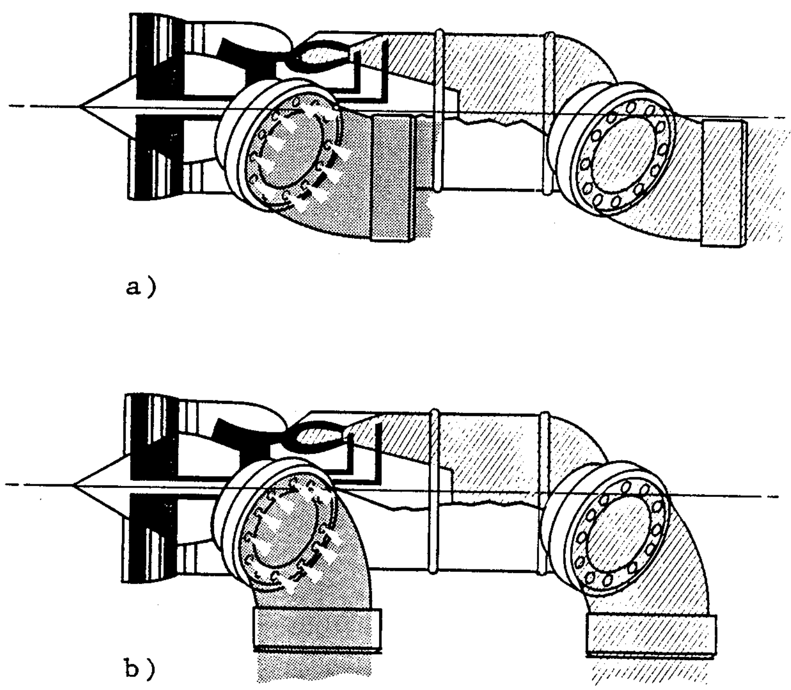

Figure 13 Vectored Thrust engine system: a) nonpowered-lift configuration, b) powered lift configuration.

In order to put the new takeoff routine to use, takeoff data for the ejector, RALS, HTF, and vectored thrust concepts were generated by running the takeoff routine in ACSYNT given mission and takeoff requirements. The data is presented in Figures 14 and 15.[9,10]

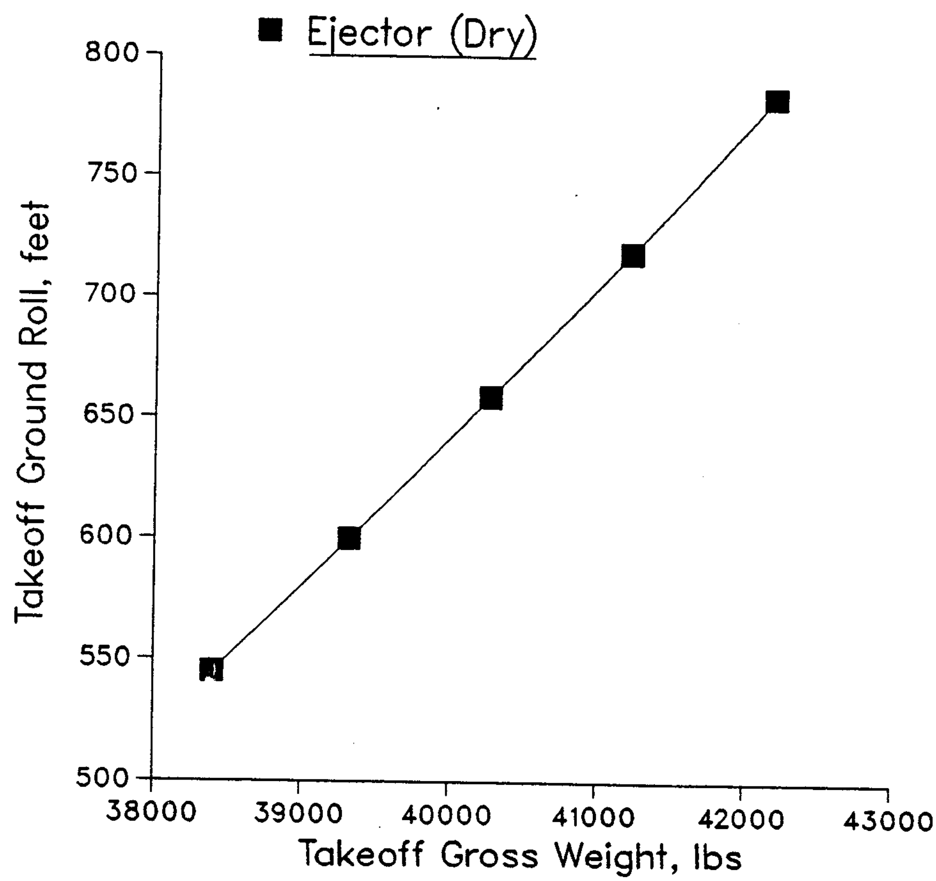

Figure 14 Ejector ground roll performance as a function of gross weight.

The variation in ground roll for the ejector as a function in gross weight is shown in Figure 14. This is for a long mission, in terms of range, lots of supersonic cruise and long loiter times. Figure 15 shows the variations in takeoff ground roll as a function in gross weight for the RALS, HTF, and vectored thrust aircraft. These aircraft all have the same mission profile, though less demanding than the mission for the ejector aircraft. Since each aircraft is in a preliminary stage of development, only preliminary conclusions can be drawn about which aircraft configuration is the best in terms of takeoff performance. Also takeoff performance is heavily dependent upon aircraft and engine sizing due to both takeoff requirements and flight performance requirements. At this point, it appears that the vectored thrust concept has the best takeoff performance.

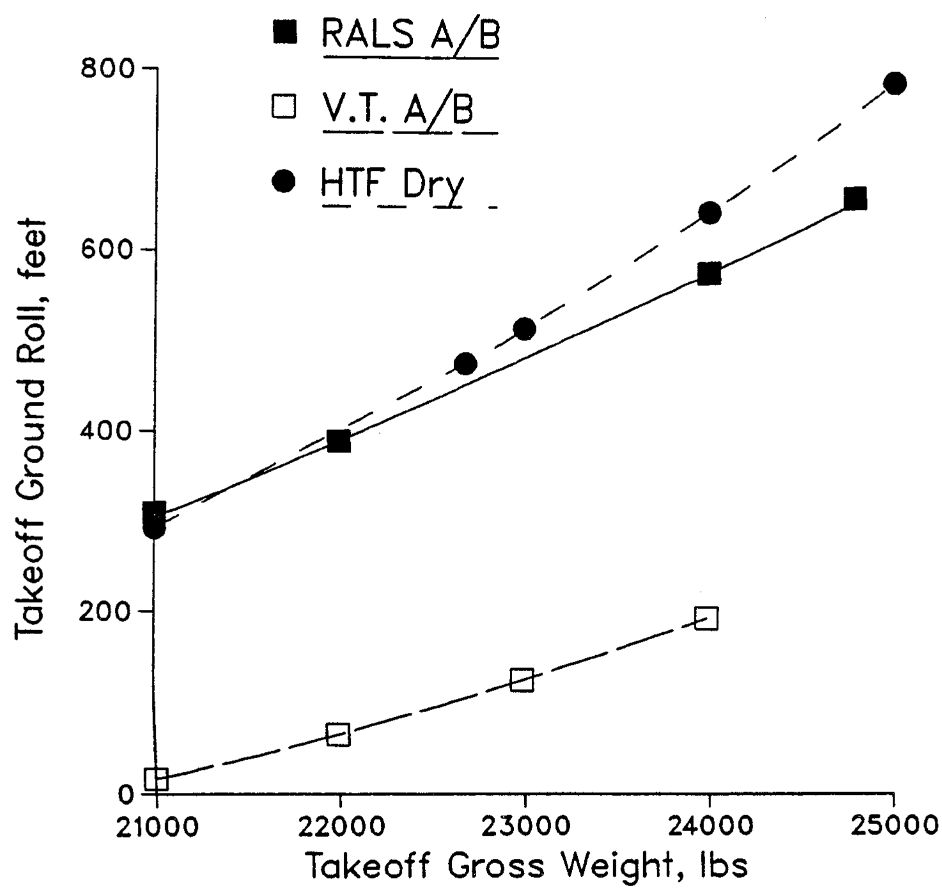

Figure 15 Takeoff ground roll comparisons as a function of gross weight.

The main point that the above analysis shows is that the new takeoff routine will produce minimum takeoff ground rolls, and though not shown, thrust vector angles to achieve that minimum roll. The conditions on takeoff were that a minimum flight path acceleration was to be 0.1 g, with a flight path angle of 3°. Differences in ground roll can be attributed to engine performance and aircraft design: wing area, C_L, C_D, tail scrape angle, nozzle locations and angle limitations, etc.

RESULTS

The new takeoff routine that was integrated into the aircraft synthesis program ACSYNT, both at NASA Ames and Cal Poly, added the capability to predict the ground run for various powered-lift aircraft designs, an ability that was lacking and should prove to be of great use. The routine also added the ability for ACSYNT to better predict ground runs for conventional takeoff aircraft--those with no thrust vectoring capability. The routine proved accurate in the case of the Harrier aircraft. Therefore, if the input data is good, the takeoff predictions should also be good.

RECOMMENDATIONS

Further enhancements/improvements of the takeoff routine might include:

1. Addition of aerodynamic moments: take into account the moment of the wing and that of the tail.
2. Add multiple engine capability.
3. Add supercirculation lift analysis: lift improvement due to blown air over the wing--either by the vectoring nozzles, a blown flap, or some other means. This addition should greatly increase the number of aircraft that could be analyzed by the routine.
4. Take into account the components of ram drag due to the angular difference between the path and engine intake.

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APPENDIX A

Level Two Takeoff Manual

DESCRIPTION

There are three takeoff routines used by ACSYNT which will be referred to as "level one", "level two", and "level three." Level one takeoff is that routine in the Trajectories Module that predicts takeoff roll based on ACSYNT only information (i.e. no module 14 input). Level two and three takeoff routines are in module 14, the Takeoff Module. Level two takeoff will predict the minimum takeoff ground roll and corresponding front nozzle angle, rear nozzle angle, and thrust split for STO powered-lift type aircraft. It can do this prediction for such aircraft as an ejector, a tandem fan, a RALS (remote augmented lift system), or a vectored thrust configuration. Besides powered lift concepts, it can predict the takeoff roll for a conventional takeoff aircraft. It can probably be used for many other types of aircraft--just keep in mind the assumptions and limitations of the takeoff routine and how they apply to a given aircraft. The main assumptions and limitations are listed below with further explanation provided under the TAKEOFF INPUT section.

1) The aircraft is represented by a point mass at the c.g.; no inertial forces are included.

2) The program assumes that the aircraft's takeoff attitude, front nozzle angle, rear nozzle angle, and thrust split are instantaneously achieved at the takeoff velocity. This can be partially compensated for by inputting a time duration, at which the velocity is held constant at the takeoff value, and the aircraft is not allowed to takeoff until the time duration is over.

3) The aircraft is balanced with thrust forces only.

4) No increased lift by circulation affects are taken into account from the engine thrust.

5) The sum of all aerodynamic moments were assumed to be zero. This means that all lift and drag forces, except ram drag, act at the c.g.

6) The rear nozzle angle can vary from 0 to 180 degrees. This is probably not true for most aircraft, but the solution to the rear nozzle angle will likely to be less that 90 degrees.

7) The front nozzle angle range can be input by the user.

8) The forward thrust varies linearly with respect to the thrust split.

9) Only single engine aircraft may be analyzed (or engine data must be that of total engine thrust if more than one, and moments caused by one engine out cannot be analyzed).

10) No ground effects are applied.

11) No reaction control system is accounted for (though this may be accounted for in the engine file).

Level three takeoff performs a simulation of an aircraft's takeoff and transition to wing-borne flight. this routine requires the actual settings, schedules, and moving rates for mechanical flaps, blown flaps (which doesn't work), thrust nozzle angle (can only have a rear nozzle--no front nozzle), and rotation velocity, along with the aircraft's total C_L and C_D information.

EXECUTION

The takeoff module (module 14) can be run in ACSYNT execution and output modes. If it is in either of these modes, it must also be in ACSYNT input. If run in ACSYNT execution it: 1) must precede the Trajectory Module (module 2) in the execution array; 2) will update the ACSYNT global common with the calculated takeoff information; and 3) will override the variables TIMTO2 and IPSTO2 from namelist TRDATA in the Trajectories Module.

If, on the otherhand, the Takeoff Module is run only in ACSYNT output, then the takeoff information calculated will not be updated into ACSYNT global common, level two takeoff output summary will be printed and level on takeoff information will be used by ACSYNT. If ACSYNT is to be updated, and the takeoff summary is required without all the debug information, run it in ACSYNT execution and output with IPDBUG = 0 (see INPUT section under Namelist MISC).

INPUT

Level two input to module 14 is as follows:

1) Enter *Namelist MISC* variables that are to have values other than the default values.
2) Enter *Namelist HILFT* variables that are to have values other than the default values.
3) Enter *formatted input* as required. Some variables may be set in Namelist HILFT that will require this additional formatted input. This additional input will be read after Namelist HILFT, but before Namelist TO.
4) Enter *Namelist TO* variables that are to have values other than the default values.

Numbers in parentheses are default values for each variable.

<u>Namelist MISC:</u>

CDGEAR (0.0)	Landing gear drag coefficient. If this formula is zero at execution, the formula CDGEAR = (0.0032/SW)*W**0.8) is used; where SW is wing area and W is aircraft weight.

CDRAMD (0.0)	Ram-drag coefficient at takeoff. If this is zero at execution, then Lewis engine deck supplied data is used.
CDRDGR (0.0)	Ram-drag coefficient during the ground roll prior to takeoff. If zero at execution, then Lewis engine deck supplied data is used.
EYEWNG (0.0)	Wing incidence angle (positive leading edge up), *degrees*.
GAMARW (0.0)	Runway slope (positive uphill), *degrees*.
HAPT (0.0)	Airport altitude, *feet*.
HOBST (50.0)	Height of obstacle to clear, *feet*. This for informational purposes only and does not affect the takeoff roll reported to ACSYNT global common. For this calculation, flight path acceleration and angle is assumed constant until the height HOBST is reached.

IPDBUG (0)	Debug print code: 0 = No extra print (print for ICALC = 3). 1 = Print during each execution (for ICALC = 2 and 3). ICALC = 1 means ACSYNT input mode. ICALC = 2 means ACSYNT execution mode. ICALC = 3 means ACSYNT output mode.
MU (0.02)	Rolling coefficient of friction. Typical values are: Concrete 0.02 to 0.03 Hard turf 0.05 Short grass 0.05 Long grass 0.10 Soft ground 0.10 to 0.30
THETAD (0.0)	Takeoff departure angle with respect to the horizontal, *degrees*.
TOVFACT (1.1)	Takeoff velocity factor: $V_{to} = V_{to}$*TOVFACT. This variable is to be used as a safety factor since the calculated V_{to} is the velocity at which the aircraft can just sustain itself--given the input constraints.

XDELFM* (0.0,0.0,0.0,0.0,0.0)	Scheduled mechanical flap deflection angles, *degrees*. **NOTE:** For level two, only the first two numbers of XDELFM are used. The first **number** is the flap angle during **ground roll**. The **second number** is the flap angle at **takeoff.** To use this variable, IAERO must = 0 in Namelist HILFT.
XNU* (0.0,0.0,0.0,0.0,0.0)	Scheduled thrust vector angles & thrust split during ground roll, *degrees*. **NOTE:** For level two (IOPT = 2), only the three values of XNU are used. XNU(1) = front nozzle angle, *deg*. XNU(2) = rear nozzle angle, *deg*. = XNU(1) if LTYPE >= 17. XNU(3) = thrust split. = 0.5 if LTYPE >= 17. Each value is for ground roll only. Level two will calculate the angles (if LTYPE > 8) and thrust split (if LTYPE < 17) at takeoff. MAKE SURE MODGND IS PROPERLY SET.

* These variables are global common variables that could be ACSYNT constraint, optimization, or design variables.

Namelist HILFT:

IAERO (1)

Aerodynamic data option:

0 = use C_L and C_D data supplied by the user. This is used if the user has the actual C_L and C_D data, or if the user wishes to use flaps or some high lift device (other than engines) for takeoff.

1 = no user supplied data. Use ACSYNT C_L and C_D data.

If = 0, the additional formatted input is read (see FORMATTED INPUT section for details).

IDATA (1)

Flap-type data code (for IAERO = 0)

1 = use mechanical flap input data.

2 = use blown flap input data (does nothing at this time).

(see FORMATTED INPUT section for details)

IOPT (2)

Takeoff routine flag:

0 = use only level three takeoff.

1 = use level two takeoff and feed answers back to level three takeoff.

2 = use only level two takeoff.

LTYPE (1) — Aircraft lift/lift-augmentor devices used.

1 = No high-lift devices (CTO).
2 = Mechanical flaps only.
3 = Blown flaps only (not used).
4 = Spoilers/speed brakes only (not used).
5 = Mechanical and blown flaps.
6 = Mechanical flaps and spoilers.
7 = Blown flaps and spoilers (not used).
8 = Mechanical & blown flaps and spoilers.
9 = Forward fan only.
10 = Forward fan and #2.
11 = Forward fan and #3.
12 = Forward fan and #4.
13 = Forward fan and #5.
14 = Forward fan and #6.
15 = Forward fan and #7.
16 = Forward fan and #8.
17 = Vectored thrust through the c.g. (thrust split = 0.5, XRAMD = 0.0, ZRAMD = 0.0).
18 = Vectored thrust and #2.

19 = Vectored thrust and #3.

20 = Vectored thrust and #4.

21 = Vectored thrust and #5.

22 = Vectored thrust and #6.

23 = Vectored thrust and #7.

24 = Vectored thrust and #8.

Note: All of the LTYPE options for LTYPE > 8 have a rotatable rear nozzle.

LFTYPE (2)

Forward fan type. Used only if LTYPE > 8.

1 = self-powered forward fan (**This does not work!**). Additional information must be input (see FORMATTED INPUT section).

2 = cruise-engine-powered forward fan. This can be a fan, ejector, or any engine-powered lift-producing device. Engine file is used as the thrust source.

NLF (1)

Number of LFTYPE lift fans. This is always 1 for level two takeoff.

Formatted Input:

For IAERO = 0 and IDATA = 1 -- Mechanical Flaps:

```
Read MFREAD  (I10)

Read NALPHA, NDELF  (2I10)

Read (XDELF(I), I=1,NDELF)  (8F10.1)

Do I=1,NALPHA

   Read XALPHA(I), (XCL(I,J), J=1,NDELF)  (8F10.1)

Enddo

If MFREAD <= 1  (CD = f(CL, DELFM)

   Read NCL  (I10)

   Read XCLX(I), (XCD(I,J), J=1,NDELF)  (8F10.1)

Else

   Do I=1,NALPHA

      Read (XCD(I,J), J=1,NDELF)  (8F10.1)

   Enddo

Endif
```

For execution, give Alpha and Flap angle (XDELFM)

Definitions of formatted input variables for flaps:

MFREAD = Lift and drag data read-in flag

<= 1 means input CD as a function of CL and DELFM

> 1 means input CD as a function of alpha and DELFM

NALPHA = # of input angle of attacks

NDELF = # of input flap angles

XDELF(I) = flap deflection angles

XALPHA(I) = angle of attack

XCL(I) = CL corresponding to XALPHA(I) and XDELF(I)

NCL = # of CL values for input

XCLX(I) = CL at XDELF(I)

XCD(I,J) = CD at the XCLX(I) and XDELF(I) value

XCD(I,J) = CD at the XALPHA(I) and XDELF(I) value

<u>For IAERO = 0 and for IDATA = 2 -- Blown Flaps</u>

There is currently an empty routine for both input and execution of blown flap data.

<u>For LFTYPE = 1 -- Self-powered lift fan</u>

```
Read NPWR  (I10)
Do I=1,NPWR
   Read PWRLVL(I), TNFAN(I), WFFAN(I)  (3F10.1)
Enddo
```

For level two THIS DOES NOT WORK PROPERLY. It will read in this data, but it will not use it properly.

<u>Definitions of formatted input variables for lift fan:</u>

NPWR = number of power level inputs

PWRLVL(I) = fan power level setting

TNFAN(I) = thrust of the fan at PWRLVL(I)

WFFAN(I) = fuel flow of the fan at PWRLVL(I)

<u>For spoiler input, the set-up is as follows:</u>

```
Read NCLSP, NDELSP  (2I10)
Read DELSP(I), I=1,NDELSP  (8F10.1)
Do I=1,NCLSP
   Read CLSP(I), (DCDSP(I,J), J=1,NDELSP)  (8F10.1)
Enddo
```

Although module 14 will read in spoiler data, it will not currently call the spoiler subroutine during ACSYNT execution. This was mainly for level three landing--which was never implemented. If it is connected to the program for execution, given DELSPL (spoiler deflection angle), and C_L of the wing, it should return the C_D of the wing.

<u>Definitions of formatted input variables for spoiler:</u>

NCLSP = # of C_L's for input

NDELSP = # of deflection angles

CLSP(I) = C_L of the wing at DELSP(I)

DCDSP(I,J) = C_D of the wing at DELSP(I)

NOTE: For all formatted input, the comment (8F10.1) or (2I10) means the length of the card (line) is 8 or 2. If there are more than 8 or two items in that input array, then just add more cards (lines) to the input structure.

Namelist TO:

ACCELM (0.1) Minimum forward acceleration desired along the flight path, *g's*.

ALPHATO (20.0) Takeoff angle of attack, *degrees*.

FANGLE (0.0) Fuselage angle with respect to the runway during ground roll, *degrees*.

FNAFT (89.0) Maximum front-nozzle aft deflection, measured perpendicular to the fuselage, *degrees*. (Maximum FNAFT is 89.0 degrees).

FNFWD (-89.0) Minimum front-nozzle forward deflection, measured perpendicular to the fuselage, *degrees*. (Minimum FNFWD is -89.0 degrees).

IPGND (2) Engine thrust level during the ground roll.

1 = use max A/B thrust.

2 = use max dry thrust (Military Power).

3 = use 95% dry thrust (Max. Continuous).

4 = use Thrust = Drag.

5 = use idle thrust.

IPROT (2) Engine thrust level at takeoff. Has the input choices as IPGND.

MODGND (4) Engine table look-up identifier during the ground roll. It has the same meaning as MMPROP (only choices 4 & 5 are tested):

4 = Lewis engine table look-up.

Engine mode = axial thrust.

5 = Lewis engine table look-up.

Engine mode = vertical thrust.

MODROT (4)	Engine table look-up identifier at takeoff. Same inputs as MODGND. **NOTE:** An example of the use of MODGND and MODROT; set MODGND = 4 and MODROT = 5. This means that the ground roll is performed in mode 1 configuration (axial thrust mode), then at rotation switches to mode 2 configuration (vertical thrust mode).
ROTATE (0.0)	Time the aircraft is held on the ground at the takeoff velocity, *seconds*. Can be used to simulate time for the nozzles to rotate to the takeoff angle and/or time for the engine mode to change.
SPLITM (0.5)	Maximum thrust split. For forward fan configurations only (LTYPE's 9 to 16). Thrust split = forward thrust/total thrust.
THTSCP (20.0)	Fuselage tail scrape angle, *degrees*.
VR (75.0)	Takeoff rotation speed, *knots*. For level two, this is the first guess of the takeoff velocity; gets updated after each call to this module.
XFRONT (1.0)	Distance of the front-thrust force forward of the c.g. along the fuselage, *feet*.
XRAMD (0.0)	Distance of the ram-drag force forward of the c.g. along the fuselage, *feet*.
XREAR (1.0)	Distance of the rear-thrust force aft of the c.g. along the fuselage, *feet*.

ZFRONT (0.0)	Height of the front-thrust force above the c.g. waterline, *feet*.
ZRAMD (0.0)	Height of the ram-drag force above the c.g. waterline, *feet*.
ZREAR (0.0)	Height of the rear-thrust force above the c.g. waterline, *feet*.

OUTPUT

The summary output produced when module 14 is run in ACSYNT output with IPDBUG = 0, or run in ACSYNT execution with IPDBUG = 1, is self explanatory. The only items that need mentioning are error messages that the routine may give.

There are two type of messages that the module outputs if something went wrong or may have went wrong; these are the *WARNING* messages and *NOTICE* messages. A search for these two words (*WARNING* and *NOTICE*) will tell the user if the program had troubles in predicting the takeoff parameters. A *WARNING* message means that the program couldn't converge on the solution (got stuck in a loop) and/or the solution couldn't be found. It also means that the output is bad and gives a default takeoff velocity of 200*TOVFACT knots and sets nozzle angles equal to zero. If also run in ACSYNT execution mode, then it gave ACSYNT bad takeoff information.

On the otherhand, a *NOTICE* message means that the input didn't make sense or there were conflicting values in which the program took corrective action. These messages should be observed to make sure that the action the computer took was what you intended.

APPENDIX B

Equation Development

The development of the equations used in the takeoff module written for ACSYNT is fairly straight forward, though the equations are often complex. The three main equations are balance, force along the flight path, and force perpendicular to the flight path.

Balance equation

The first equation (same as Eq. (1) of text) is the balance equation about the aircraft's c.g. created by the ram-drag vector, front thrust vector, and rear thrust vector. The moments are summed about the c.g. (Fig. 2) with positive moments in the clockwise direction and positive forces acting in the direction of the forward flight path.

$$\mathrm{THRSTU*SPLIT*DFRONT*}\sin(\theta_F-\beta_7)-\mathrm{RAMD*DRAMD*}\sin(\gamma-\theta_{FUS}-\beta_9) \quad \text{(B1)}$$

$$= \mathrm{THRSTU} * (1-\mathrm{SPLIT}) * \mathrm{DREAR} * \sin(\theta_R+\beta_8) \quad \text{where,}$$

$$\mathrm{DFRONT} = \{(X_F)^2+(Z_F)^2\} \quad \text{(B1a)}$$

$$\mathrm{DREAR} = \{(X_R)^2+(Z_R)^2\} \quad \text{(B1b)}$$

$$\mathrm{DRAMD} = \{(X_{RD})^2+(Z_{RD})^2\} \quad \text{(B1c)}$$

$$\beta_7 = \mathrm{atan}(\frac{Z_F}{X_F}) \quad \text{(B1d)}$$

$$\beta_8 = \text{atan}(\frac{Z_R}{X_R}) \tag{B1e}$$

$$\beta_9 = \text{atan}(\frac{Z_{RD}}{Z_{RD}}) \tag{B1f}$$

Force perpendicular to the flight path

The second equation (same as Eq. (2) in text) is the sum of the forces perpendicular to the flight path. This summation is set to zero, insuring that the aircraft is on the specified flight path:

$$\begin{aligned} FAZ = 0 = & C_L*q*S_{REF} - W*Cos(\gamma) + \\ & THRSTU*SPLIT*Sin(\theta_{FUS}+\theta_F-\gamma) + \\ & THRSTU*(1.0-SPLIT)*Sin(\theta_{FUS}+\theta_R-\gamma) \end{aligned} \tag{B2}$$

Force along the flight path

The third equation (same as Eq. (3) in text) is the sum of the forces along the specified flight path. This summation is set equal to the input flight path acceleration times the aircraft weight:

$$\begin{aligned} FA = W*ACCELM = & - C_D*q*S_{REF} - RAMD - W*Sin(\gamma) + \\ & THRSTU*SPLIT*Cos(\theta_{FUS}+\theta_F-\gamma) + \\ & THRSTU*(1.0-SPLIT)*Cos(\theta_{FUS}+\theta_R-\gamma) \end{aligned} \tag{B3}$$

In order to solve for the rear-nozzle angle (θ_F) and the thrust split (SPLIT), Eqs. (B1) and (B3) are used. Rearranging Eq. (B1) for rear-nozzle angle yields;

$$\theta_R = \text{ArcSin}((\frac{THRSTU*SPLIT*DFRONT*Sin(\theta_F-\beta_7) - RAMD*DRAMD*Sin(\gamma-\theta_{FUS}-\beta_9)}{THRSTU*(1.0-SPLIT)*DREAR})) - \beta_8 \tag{B4}$$

Similarly Eq. (B3) yields,

$$\theta_R = \text{ArcSin}\left(\left(\frac{W*ACCELM + C_D*q + RAMD + W*Sin(\gamma) - THRSTU*SPLIT*Cos(\theta_{FUS}+\theta_F-\gamma)}{THRSTU*(1.0-SPLIT)}\right)\right)-\theta_{FUS}+\gamma \tag{B5}$$

Equating rear-nozzle angles, Eqs. (B4), or (4) and (B5), we get

$$\text{ArcCos}\left(\left(\frac{W*ACCELM + C_D*q + RAMD + W*Sin(\gamma) - THRSTU*SPLIT*Cos(\theta_{FUS}+\theta_F-\gamma)}{THRSTU(1.0-SPLIT)}\right)\right) - \theta_{FUS} + \gamma$$
$$= \tag{B6}$$
$$\text{ArcSin}\left(\left(\frac{THRSTU*SPLIT*DFRONT*Sin(\theta_F-\beta_7) - RAMD*DRAMD*Sin(\gamma-\theta_{FUS}-\beta_9)}{THRSTU*(1.0-SPLIT)*DREAR}\right)\right) - \beta_8$$

Now taking the sine of both sides and solving for SPLIT,

$$SPLIT = \frac{\{Sin[ArcCos(LHS)-\theta_{FUS}+\gamma+\beta_8]\} * \{THRSTU*(1.0-SPLIT)*DREAR\} + RAMD*DRAMD*Sin(\gamma-\theta_{FUS}-\beta_9)}{THRSTU*DFRONT*Sin(\theta_{FUS}-\beta_9)} \tag{B7}$$

This is the same equation as Eq. (6) of the text.

Velocity can now be calculated one of two ways depending on input. If ram-drag is to be calculated from the engine file, then RAMD = THRSTU-THRUST and

$$V^2 = \frac{W + RAMD*Sin(\gamma) - THRSTU*SPLIT*Cos(90-\theta_F-\theta_{FUS}) - THRSTU*(1.0-SPLIT)*Sin(\theta_{FUS}+\theta_R)}{0.5*\rho*S_{REF}*(C_L*Cos(\gamma)-C_D*Sin(\gamma)} \tag{B8a}$$

If ram-drag is to be given by the user, then RAMD = CDRAMD * $0.5*\rho*V^2*S$ and

$$V^2 = \frac{\begin{array}{l} W - THRSTU*SPLIT*Cos(90-\theta_F-\theta_{FUS}) \\ - THRSTU*(1.0-SPLIT)*Sin(\theta_{FUS}+\theta_R) \end{array}}{0.5*\rho*S_{REF}*(C_L*Cos(\gamma)-(C_D+CDRAMD)*Sin(\gamma)} \qquad (B8b)$$

To check on the acceleration along the flight path, Eq. (3) can be rewritten as:

$$ACCELF = \frac{\begin{array}{l} - C_D*q - RAMD - W*Sin(\gamma) \\ + THRSTU*SPLIT*Cos(\theta_{FUS}+\theta_F-\gamma) \\ + THRSTU*(1.0-SPLIT)*Cos(\theta_{FUS}+\theta_R-\gamma) \end{array}}{W} \qquad (B9)$$

The acceleration along the flight path (ACCELF) will always be greater than or equal to the minimum acceleration along the flight path, if SPLIT is less than the best thrust split for shortest takeoff due to the balance equation (equation 1).

Ground roll calculation

The ground roll calculation uses Eqs. (B10a) and (B10b), or Eqs. (4a) and (4b) in the text. This is just the integration of the V/a with respect to the velocity, where "V" is the aircraft's velocity and "a" is the acceleration at some point in time.

$$SG = \int_0^{V_{TO}} \frac{V}{a}\, dV \qquad (B10a)$$

where,

$$a = \frac{\begin{array}{l} [THRSTH-MU*(W-THRSTV)-RAMD]-[C_D-MU*C_L]*q*S_{REF} \\ - W*\gamma_{RW} \end{array}}{W/g} \qquad (B10b)$$

Vectored thrust through the c.g.

This routine is very similar to the previous routine, except now thrust split (SPLIT) is set to 0.5 and $\theta_F = \theta_R$. Then from equation 4;

$$\theta_R = \mathrm{ArcSin}\left(\frac{W*\mathrm{Cos}(\gamma) - C_L*q}{THRSTU}\right) \tag{B11}$$

and from Eq. (3) with RAMD = THRSTU - THRUST;

$$V^2 = \frac{THRSTU*\mathrm{Cos}(\theta_{FUS}+\theta_R-\gamma) - RAMD - W*(\mathrm{Sin}(\gamma)-ACCELM)}{0.5*\rho*S_{REF}*C_D} \tag{B12a}$$

Then with RAMD = $0.5*\rho*V^2*S_{REF}*CDRAMD$;

$$V^2 = \frac{THRSTU*\mathrm{Cos}(\theta_{FUS}+\theta_R-\gamma) - W*(\mathrm{Sin}(\gamma)+ACCELM)}{0.5*\rho*S_{REF}*(C_D+CDRAMD)} \tag{B12b}$$

Conventional takeoff (CTO)

For CTO aircraft, the takeoff routine, given all the assumptions and limitations, becomes very simple. Again for RAMD = THRSTU - THRUST;

$$V^2 = \frac{2*W}{\rho*(C_L*\mathrm{Cos}(\gamma)-C_D*\mathrm{Sin}(\gamma))} \tag{B13a}$$

For RAMD = $0.5*\rho*V^2*CDRAMD*S$;

$$V^2 = \frac{2*W}{\rho*(C_L*\mathrm{Cos}(\gamma)-(C_D+CDRAMD)*\mathrm{Sin}(\gamma))} \tag{B13b}$$

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16. Abstract

Takeoff predictions for powered-lift short takeoff (STO) and conventional takeoff (CTO) aircraft have been added to NASA AMES Research Center's Aircraft Synthesis (ACSYNT) code. The new computer code predicts the aircraft engine and nozzle settings required to achieve the minimum takeoff roll. As a test case, the code predicted takeoff ground rolls and nozzle settings for the YAV-8B Harrier that compared well with measured values. Brief analysis of takeoff performance for an Ejector, Remote Augmented Lift, Hybrid-Tandem Fan, and Vectored Thrust STO aircraft using the new routine will be presented.

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